ECONOMIC RESEARCH
FEDERAL RESERVE BANK OF ST. LOUIS

WORKING PAPER SERIES

The Daily and Policy-Relevant Liquidity Effect

Authors	Daniel L. Thornton
Working Paper Number	2007-001B
Revision Date	December 2006
Citable Link	https://doi.org/10.20955/wp.2007.001
Suggested Citation	Thornton, D.L., 2007; The Daily and Policy-Relevant Liquidity Effect, Federal Reserve Bank of St. Louis Working Paper 2007-001. URL https://doi.org/10.20955/wp.2007.001

Federal Reserve Bank of St. Louis, Research Division, P.O. Box 442, St. Louis, MO 63166

The Daily and Policy-Relevant Liquidity Effects

Daniel L. Thornton
Federal Reserve Bank of St. Louis
Phone (314) 444-8582
FAX (314) 444-8731
Internet Address: thornton@stls.frb.org

November 2007

Abstract

The phrase "liquidity effect" was introduced by Milton Friedman (1969) to describe the first of three effects on interest rates caused by an exogenous change in the money supply. The lack of empirical support for the liquidity effect using monthly and quarterly data led Hamilton (1997) to suggest that more convincing evidence of this effect could be obtained using daily data—estimating the daily liquidity effect. This paper investigates the implications of the daily liquidity effect for Friedman's (policy-relevant) liquidity effect using a comprehensive model of the Fed's daily operating procedure. The evidence indicates that it is no easier to find convincing evidence of a policy-relevant liquidity effect using daily data than it has been using lower frequency data.

JEL Classification: E40, E52
Key words: liquidity effect, federal funds rate, monetary policy, operating procedure, FOMC

The views expressed here are the author's and do not necessarily reflect the views of the Board of Governors of the Federal Reserve System or the Federal Reserve Bank of St. Louis. I would like to thank Jim Hamilton and Sherry Edwards for useful comments and Jonathan Ahlbrecht, John McAdams, and Daniel McDonald for helpful research assistance.

1. Introduction

The phrase "liquidity effect" was first used by Milton Friedman (1969) to describe the first of three effects on interest rates caused by an exogenous change in the supply of money.[1] Despite its prominent role in theories of the monetary policy transmission mechanism, there has been very little evidence of an economically meaningful and statistically significant liquidity effect.[2] Suggesting that previous attempts to identify the liquidity effect have been unsuccessful because low frequency data necessarily mixes together the effects of policy on economic variables with the effects of economic variables on policy, Hamilton (1997) sought to develop a "more convincing measure of the liquidity effect" by estimating the response of the federal funds rate to exogenous reserve supply shocks using daily data, i.e., by estimating the daily liquidity effect. Thornton (2001a) showed that the estimated daily liquidity effect that Hamilton reported was the consequence of a few extreme observations and that there was no evidence of a daily liquidity effect using Hamilton's model and methodology for sample periods prior to and after Hamilton's. Recently, Carpenter and Demiralp (2006) report evidence of a daily liquidity effect using a more complete model of the operating procedure of the Trading Desk of the Federal Reserve Bank of New York (hereafter, Desk) than Hamilton's. They also use a measure of the reserve supply shock made each day in conducting open market operations rather than the estimate of the reserve supply shock used by Hamilton.

[1] The other two are called the "income" and "price expectation" or "inflation expectation" effects (e.g., Friedman, 1969; and Gibson, 1970a,b). These effects have roots in classical economics (e.g., Humphrey, 1983a,b). Because of the inflation expectation effect, an exogenous change in money growth eventually leads to higher, rather than lower, equilibrium nominal interest rates.

[2] The empirical literature on the liquidity effect dates back at least to Cagan and Gandolfi (1969) and Gibson (1970a,b).

While they claim their results have implications for the policy-relevant liquidity effect, neither Hamilton (1997) nor Carpenter and Demiralp (2006) explicitly model the structural relationship linking the daily and policy-relevant liquidity effects. This paper fills this gap in the literature by analyzing the relationship between the daily and policy-relevant liquidity effect using a comprehensive model of the Desk's operating procedure. The analysis shows that because of specific features in the Desk's operating procedure, the Fed's system of reserve requirements, and other factors, the relationship between the daily liquidity effect and the policy-relevant liquidity effect is neither simple nor direct.

The model is estimated using Carpenter and Demiralp's reserve shock measure. The empirical evidence suggests that it is no easier to find convincing evidence of a policy-relevant liquidity effect using high-frequency daily data than it has been using monetary and reserve aggregates at the monthly or quarterly frequencies.

The remainder of the paper is divided into three sections. Section 2 investigates the relationship between the daily liquidity effect and the liquidity effect relevant for monetary policy using a detailed model of the Desk's operating procedure. Section 3 estimates the model developed in Section 2 using daily data and Carpenter and Demiralp's reserve supply shock measure. The conclusions are presented in Section 4.

2. The Policy-Relevant and Daily Liquidity Effects

Milton Friedman (1969) termed the first of three effects of an exogenous change in the supply of money on nominal interest rates the "liquidity effect." Friedman's policy-relevant liquidity effect stems directly from the demand for money, i.e.,

(1) $$M_t^d = f(i_t, y_t),$$

where M_t^d denotes the demand for money, which, for purposes of illustration, is a simple function of a nominal interest rate, i_t, and nominal income, y_t. Because individuals economize on their holding of money when interest rates rise, $\partial f / \partial i < 0$.

Equilibrium requires that the supply of money, M_t^s (which, for simplicity, is assumed to be exogenously controlled by the Fed) equals demand, i.e.,

(2) $$M_t^s = f(i_t, y_t).$$

The policy-relevant liquidity effect is the initial effect of an exogenous change in the money supply on the interest rates and is given by

(3) $$di_t / dM^s = (\partial f / \partial i)^{-1},$$

where it is assumed that neither nominal income nor inflation expectations respond immediately to the Fed's actions. Friedman (1969) called (3) the "liquidity effect."

Vast empirical evidence indicates that the demand for money is negatively related to the interest rate and is interest inelastic. This implies that a small exogenous change in the supply of money should cause a relatively large response in interest rates, i.e., the policy-relevant liquidity effect should be relatively large. Consequently, the inability of researchers to find a statistically significant and economically meaningful liquidity effect is puzzling and is referred to as the "liquidity puzzle."[3]

Among other things, the failure to find evidence of the liquidity effect using low frequency monetary and reserve aggregates has been attributed to the response of nominal income or inflation expectations to money supply shocks or to the inability of researchers to isolate exogenous monetary shocks. Researchers have attempted to overcome these problems using structural vector autoregressions (SVARs). The

[3] See Strongin (1995).

recursive SVAR, or RSVAR, has been particularly popular in this literature. SVAR models have been estimated using a variety of monetary and reserve aggregates. An extensive survey of this literature by Pagan and Robertson (1995) shows that it is difficult to find convincing evidence of a liquidity effect using any aggregate other than nonborrowed reserves. Coleman, Gilles and Labadie (1996) point out that evidence of a liquidity effect using nonborrowed reserves may be a consequence of the Desk's efforts to offset the effect of changes in discount window borrowing. Thornton (2001b) confirmed this by showing that the estimated liquidity effect using nonborrowed reserves is a consequence of the interest sensitivity of discount window borrowing and Desk's operating procedure under either monetary aggregate or funds rate targeting. He shows that this "liquidity effect" using nonborrowed reserves vanishes in the early 1980s when borrowing declined dramatically and became relatively interest insensitive.

The failure of researchers to generate evidence of a statistically significant and empirically relevant liquidity effect using monthly or quarterly data led Hamilton (1997) to suggest that the failure of the RSVAR approach likely stems from the fact that it "claims to uncover…innovations in Fed policy, defined as a change in a policy variable that is deliberately induced by Federal Reserve actions that could not have been anticipated on the basis of earlier available information." Hamilton then noted that changes in Fed policy are frequently due to information about "current or future values of output, inflation, exchanges rate, or other magnitudes," so that "the correlation between such a 'policy innovation' and the future level of output of necessity mixes together the effect of policy on output with the effect of output forecasts on policy."[4]

[4] Hamilton (1997), p. 80.

In any event, given the difficultly of identifying truly exogenous monetary policy shocks at lower frequencies, Hamilton (1997) attempted to provide evidence of a policy-relevant liquidity effect by estimating the response of the funds rate to easier-to-identify reserve supply shocks measured at the daily frequency. Specifically, using a simple model of the Desk's operating procedure he estimated the response of the federal funds rate to a reserve supply shock, which he estimated from a model of the Treasury's deposits at the Fed.

2.1 The Relationship between the Policy-Relevant and Daily Liquidity Effects

The relationship between the daily and policy-relevant liquidity effects is a consequence of the fact that the Fed imposes reserve requirements on components of money so that the demand for reserves is directly linked to the demand for money, i.e.,

(4) $$R_t^d = rrM_t^d = rrf(i_t, y_t),$$

where R_t^d denotes reserve demand and rr denotes the Federal Reserve imposed reserve requirement. Because of (4), it is possible to estimate the policy-relevant liquidity effect by estimating the response of interest rates to an exogenous change in the supply of reserves. Moreover, since the response will be identical whether the shock to reserves is due to an error the Desk makes in conducting daily open market operations or is monetary policy-induced, the there is no identification problem. It is sufficient to identify a shock to reserve supply from any source.

The relationship between the policy-relevant and daily liquidity effects depends on the Desk's daily operating procedure, which has remained essentially the same since at least the early 1970s. Conceptually, the operating procedure is simple. Each day the Desk estimates the quantity of reserves that banks will demand over a maintenance period ending every other Wednesday, called settlement Wednesday.[5] The Desk also estimates the quantity of reserves that will be supplied if the Desk conducts no open market operations that day.[6] If the former estimate exceeds the latter, the operating procedure suggests that the Desk add reserves through an open market purchase. If the former is smaller than the latter, the procedure suggests that reserves be drained through an open market sale.

Specifically, the Desk estimates the demand for total reserves, i.e.,

$$(5) \qquad E_{t-1}TR_t^d = E_{t-1}rrf(i_t, y_t) + E_{t-1}ER_t^d ,$$

where TR_t^d denotes the demand for total reserves, ER_t^d denotes the demand for excess reserves, and E_{t-1} denotes the expectation operator conditional on information available before that day's open market operation.

The supply of reserves available is given by

$$(6) \qquad TR_t^s = B_t + BR_t + F_t + OMO_t ,$$

where B_t denotes the Fed's holding of government debt prior to that day's open market operation, BR_t denotes bank borrowing at the discount window, F_t denotes autonomous factors that affect reserve supply—currency in circulation, the Treasury's balance at the Fed, the float, etc.—and OMO_t denotes the amount of open market purchases or sales conducted by the Desk that day.[7]

---

[5] Until October 1979 the estimate of demand was conditional on the objective or target for the federal funds rate. From October 1979 to September 1982, the estimate was conditional on the objective for the growth rate of the M1 monetary aggregate. Beginning in September 1982, the Fed claimed that the estimate was conditional on an objective for borrowed reserves; however, Thornton (2006) provides evidence from FOMC transcripts suggesting that the real objective was the federal funds rate. Today the objective is unquestionably the federal funds rate.

[6] A more detailed analysis of the Desk's operating procedure can be found in Feinman (1993) and Thornton (2001b, 2007).

[7] Borrowing (and later the initial borrowing assumption) refers to seasonal plus adjustment borrowing.

Each day the Desk estimates the supply of reserves that will be available if the Desk conducts no open market operations. The Desk essentially knows the magnitude of B_t, but must make an estimate the F_t. The Desk does not estimate borrowing, but rather applies the Federal Open Market Committee (FOMC) determined borrowing assumption, called the initial borrowing assumption (IBA_t).[8] The estimate of reserve supply if the Desk conducts no open market operations is

(7) $$E_{t-1}TR_t^s = B_t + E_{t-1}F_t + IBA_t,$$

where $E_{t-1}F_t$ denotes the Desk's estimate of autonomous factors. The amount of the open market operations suggested by the Desk's operating procedure—the operating procedure-determined open market operation ($OPDOMO_t$)—is given by

(8) $$OPDOMO_t = (E_{t-1}rrf(i_t, y_t) + E_{t-1}ER_t^d) - (B_t + E_{t-1}F_t + IBA_t).$$

If $OPDOMO_t$ is positive, the procedure directs the Desk to purchase government securities; if it is negative, the procedure indicates government securities should be sold.

If the Desk follows the operating procedure exactly, $OMO_t = OPDOMO_t$. The operating procedure is intended to provide the Desk guidance: Judgment is used to conduct each day's open market operation. Indeed, over most of the period examined here, the Desk almost never followed the operating procedure exactly (e.g., Thornton, 2007). To allow for this fact, let

(9) $$OMO_t = OPDOMO_t + k_t,$$

Extended credit borrowing is treated separately, as one of the autonomous factors affecting reserve supply.

[8] The *IBA* was changed relatively infrequently and, most often, when the funds rate target was changed. Thornton (2006) shows that the *IBA* was last mentioned in discussing monetary policy during a conference call on January 9, 1991. However, it remained part of the Desk's formal operating procedure until at least 1996.

where k_t denotes the amount by which actual open market operations differ from the open market operations recommended by the operating procedure.

Reserve market equilibrium requires

(10) $$rrf(i_t, y_t) + ER_t^d = B_t + F_t + BR_t + OMO_t .$$

Substituting (8) and (9) into (10) yields

(11) $$\begin{aligned} &rrf(i_t, y_t) = \\ &\quad E_{t-1}rrf(i_t, y_t) - (ER_t^d - E_{t-1}ER_t^d) - (F_t - E_{t-1}F_t) - (BR_t - IBA_t) + k_t . \end{aligned}$$

The interest rate that equates the reserve market is the federal funds rate, ff_t which the FOMC has been targeting since 1982.[9] Hence, the Desk's expectation of reserve demand is conditional on the FOMC's target for the funds rate. These observations imply that

(12) $$E_{t-1}rrf(ff_t, y_t) = rrE_{t-1}f(ff_t^*, E_{t-1}y_t),$$

where ff_t^* denotes the FOMC's target for the federal funds rate. Note that (12) can be rewritten as

(13) $$\begin{aligned} &rrf(ff_t, y_t) = \\ &rrE_{t-1}f(ff_t^*, y_t) - (ER_t^d - E_{t-1}ER_t^d) - (F_t - E_{t-1}F_t) - (BR_t - IBA_t) + k_t . \end{aligned}$$

The daily liquidity effect is given by

(14) $$\frac{\partial ff_t}{\partial(F_t - E_{t-1}F_t)} = \frac{1}{rr(\partial f / \partial ff_t)} < 0 .$$

2.2 Desk Operations and Estimates of the Daily Liquidity Effect

The details of Desk operations have implications for estimates of the daily liquidity effect. Following Hamilton (1997) assume that the demand is linear, i.e.,

[9] See Thornton (1988, 2006) for the relevant evidence.

(15) $$f(ff_t, y_t) = -\beta ff_t + \alpha y_t + \eta_t,$$

where α and β are positive fixed parameters and η_t denotes an *i.i.d.* random disturbance with mean zero and a constant variance. With these assumptions, (13) can be rewritten as

(16) $$\begin{aligned} ff_t = -(1/rr\beta)^{-1}[-rr\tilde{\beta} ff_t^* + (F_t - E_{t-1}F_t) + (BR_t - IBA_t) \\ -(rr\alpha y_t - rr\tilde{\alpha}\tilde{y}_t) - (ER_t - E_{t-1}ER_t^d) + k_t - \eta_t], \end{aligned}$$

where ~ denotes the Desk's estimate of the corresponding parameter or variable.

The relationship between the daily liquidity and policy relevant liquidity effects depends on rr. Hence, it is important to note that there were two major reductions in reserve requirements during the past two decades. The first occurred in December 1990 and the second in April 1992.[10] There have been other changes in the Fed's reserve account procedures that are very small and, consequently, of less concern.

More important, however, is the endogenous change in effective reserve requirements which started in 1994, as banks began sweeping their retail transactions deposit accounts to reduce their effective reserve requirement (e.g., Anderson and Rasche, 2001). The result was a significant reduction in effective reserve requirements and a significant rise in the number of nonbound banks, i.e., banks that satisfy their reserve requirements with vault cash.[11] The ability of banks to satisfy their reserve requirement with vault cash severs the contemporaneous link between money demand and reserve demand. Consequently, estimates of the daily liquidity effect for nonbound

[10] Effective December 13, 1990, the 3 percent reserve requirement on non-transaction liabilities was reduced to 1.5 percent for weekly reporters; and effective December 27, 1990, the 1.5 percent reserve requirement on non-transaction liabilities was reduced to zero for weekly reporters. The combined effect of these actions reduced required reserves by an estimated \$13.2 billion. While not reported here, these changes appear to have had no important effect on the estimates of the daily liquidity effect reported in Section 3.

[11] See Anderson and Rasche (2001) for more details on the effects of retail sweep programs.

banks have no implication for the policy-relevant liquidity effect. This is extremely important because reserve demand can be interest sensitive for other reasons.

This problem is acute after July 1998 when the Fed reintroduced lagged reserve accounting. Beginning with the maintenance period that began on July 30, 1998, there is a full two-maintenance-period lag in the reserve accounting system, i.e., reserve requirements for the current maintenance period are determined by deposit balances held during the fourteen-day period two maintenance periods previous. Lagged reserve accounting does not imply that there is no response of the funds rate to a reserve supply shock. Banks are still required to hold reserves and, hence, have an incentive to economize on holding non-interest-bearing deposits with the Fed. Lagged reserve accounting severs the contemporaneous link between reserve demand and money demand. Hence, evidence of a daily liquidity effect after July 1998 (e.g., Carpenter and Demiralp, 2006) is not evidence of a policy-relevant liquidity effect.

The fact that reserve demand is interest sensitive even when there is no direct link between money demand and reserve demand arises in other situations as well. Indeed, Thornton (2001a) argued that, because of the two day lag in the Fed's system of "contemporaneous" reserve accounting in effect from March 1984 to July 1998, there was no relationship between the daily and policy-relevant liquidity effect on the last two days of the maintenance period before July 1998.[12] Specifically, during this period, a bank's maintenance-period reserve requirement was based on its holding of deposit balances during a two-week period ending two days prior to the end of the current maintenance period, implying that reserve demand is independent of money demand on

[12] From 1968 to March 1984 there was a one-maintenance-period lag in the Fed's system of reserve accounting.

the last two days of the maintenance period.

Analyses by Clouse and Dow (2002) and Bartolini, Bertola, and Prati (2002) show that reserve demand may be related to money demand on the last two days of the maintenance period if individual banks behave optimally with respect to the reserve carryover provision.[13] These models do not include the costs of operating such procedures. These costs may be large relative to the cost of satisfying a reserve shortfall at the end of the maintenance period through the discount window or some other means.[14] Consequently, it is not clear that such intense reserve management—though technically feasible—is economically viable.[15] In any event, even if banks behave optimally, the relationship between the daily and policy-relevant liquidity effects would be affected by the fact that reserve demand on these days would also be affected by the carryover provision. Consequently, the extent to which estimates of the response of the funds rate to a reserve supply shock on the last two days of the maintenance period provide evidence of the policy-relevant liquidity effect is uncertain.

The relationship between the daily and policy-relevant liquidity effects also can be distorted on days when there are idiosyncratic shocks to the funds rate. Some of these events, such as the last days of the month, quarter, year, or reserve settlement days are well known. Others appear to be associated with events that are less easily identified. Thornton (2001a) has shown that this distortion can be large on days when there are unusually large shocks to the funds rate. Hence, special care is taken in estimating the

---

[13] I would like to thank Jim Hamilton for pointing out this possibility to me.

[14] For example, the one-day cost of paying a 1-percentage-point premium on a $100 million dollar reserve shortfall is $2,739.73.

[15] There is also no direct evidence that banks actually implement such procedures. Indeed, anecdotal evidence from reserve account managers of two very large New York banks in the late 1990s suggests that these banks did not rely on such procedures to manage their reserves.

daily liquidity effect on those days.

Also note that the dependent variable in (17) is ff_t and not $ff_t - ff_t^*$, as in Carpenter and Demiralp (2006) or Δff_t as in Hamilton's (1997). The appropriate dependent variable is $ff_t - ff_t^*$ if and only if $\tilde{\beta} = \beta$, i.e., the Desk correctly estimates the interest elasticity of money demand.

Finally, as Hamilton (1997) and Carpenter and Demiralp (2006) note, a necessary condition for obtaining unbiased estimates of the daily liquidity effect is that reserve supply shocks be uncorrelated with shocks to money demand, η_t. However, (16) shows that $F_t - E_{t-1}F_t$ must also be uncorrelated with $BR_t - IBA_t$, k_t, $ER_t^d - E_{t-1}ER_t^d$, and $rr\alpha y_t - rr\tilde{\alpha}\tilde{y}_t$—variables not included in previous estimates of the daily liquidity effect.

3. Estimates of the Daily Liquidity Effect

This section estimates the daily liquidity effect based on the model developed in Section 2. The analysis employs an EGARCH (1, 1) model. The EGARCH model, which is in the class of autoregressive conditional heteroskedastic (ARCH) models developed by Engle (1982), was introduced by Nelson (1991). The specification takes the general form

(17) $$ff_t = X_t\beta + \varepsilon_t, \quad t = 1, 2, ..., T$$

where X_t denotes a 1-by-k vector of k regressors and β denotes the corresponding k-by-1 vector of coefficients. The variance of ε_t, σ_t^2, is assumed to be conditionally heteroskedastic. Specifically,

(18) $$\log\sigma_t^2 = \xi + \gamma \left|\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\right| + \psi\frac{\varepsilon_{t-1}}{\sigma_{t-1}} + \varsigma\log\sigma_{t-1}^2 + Z_t\delta + \omega_t,$$

where Z_t is a 1-by-m vector of observable variables that determine the evolution of the variance and δ is a corresponding m-by-1 vector of coefficients. The coefficient ψ allows for the possibility of asymmetry in the response of shocks to the funds rate. Because ARCH models account for heteroskedasticity, they produce estimates of β that are generally more efficient than ordinary least squares.

Figure 1 presents ff_t and ff_t^* over the period January 2, 1986, through January 20, 2004. There are a number of volatility clusters typical of ARCH. Some of these are associated with well-defined events, such as the marked increases in volatility associated with the stock market crash (bracketed by the first two vertical lines) and the surprise reduction in reserve requirements in 1990 (bracketed by the third and fourth vertical lines). There is also a marked decline in volatility that appears to begin in early 2000 (denoted by the fifth vertical line), which may be associated with banks sweeping transactions deposits and changes in the FOMC's disclosure procedures. Moreover, there is a relatively large number of volatility spikes—days when the funds rate changed by a relatively large amount only to return to essentially its previous day's level the next day. These spikes are often unique to the funds rate. Some are associated with well-known events (e.g., settlement Wednesday, and the first and last days of the year, or quarter); others are not. To account for spikes in the funds rate associated with well-known events, following Hamilton and Carpenter and Demiralp, dummy variables are used for each of the 10 maintenance period days (Di, $i = 1, 2, ..., 10$); for the first and last days of the month, quarter, and year ($bom, eom, boq, eoq, boy, eoy$); for the 15th day of the month (mom); for the day before and after holidays; for the day before and after changes in the funds rate target ($bh, ah, btar, atar$); for the month of December (dec); and for the first and second week of the maintenance period ($w1$, $w2$).[16] Dummy variables are also included for the period of the 1987 stock market crash ($d1987$) and the surprise change in reserve requirements ($d1990$).[17] The error the staff of the Board of Governors makes each day in forecasting F_t is used as a proxy for reserve supply shocks and is denoted $miss$.[18] Separate estimates of the demand for required and excess reserves are made. However, because the estimate of excess reserves is changed infrequently, the error in the Board of Governors' staff estimate of total reserve demand (err_t^D) is used, where $err_t^D = (rr\alpha\, y_t - rr\tilde{\alpha}\,\tilde{y}_t) + (ER_t - E_{t-1}ER_t^d)$.[19]

The specification of the EGARCH model is similar to Hamilton's and Carpenter and Demiralp's; however, the Student's t distribution is used rather that the normal distribution to account for the thick tails in the distribution of the funds rate. Because of the introduction of sweep accounting in January 1994, initially the model is estimated over sample period January 2, 1986 though December 31, 1993. Carpenter and Demiralp found the daily liquidity effect to be nonlinear, being statistically significant for large shocks (shocks larger than \$1 billion) but not for small shocks (shocks $\leq$ \$1 billion). Hence, $miss$ is partitioned into large shocks ($miss_t^{\lg}$) and small shocks ($miss_t^{sm}$) using their criterion. Because of the two-day lag in the Fed's system of reserve requirements

[16] If the 15th falls on a weekend or a holiday, mom takes on the value of 1 on the business day closest to the middle of the month.

[17] $d1987$ takes on the value 1 from the first day of the stock market crash, October 19, 1987, through December 31, 1987, and zero elsewhere. $d1990$ takes on the value 1 from the first settlement Wednesday affected by the changes, December 13, 1990, through February 28, 1991, and zero elsewhere.

[18] The Board Staff's estimate is a proxy because in reality, the staffs of the Board and the New York Fed make independent estimates of the autonomous factors. The Treasury makes an independent estimate of one of the factors, namely, its balance at the Fed. Exactly how these estimates are combined each day in conducting open market operations is unclear. See Thornton (2004) for further details.

[19] Not only was the estimate changed infrequently, but often it was increased for a short period of time and then returned to its former level. In contrast, the estimate of the demand for required reserves was typically changed six times during each two-week maintenance period.

during this period, settlement days are partitioned into the last two days of the maintenance period ($l2d$) and all other days ($nl2d$).[20] Also, because the effect of reserve supply shocks on the funds rate will be different on days when the funds rate target is changed, dummy variables for days when the target was changed ($d\Delta ff_t^*$) and other days ($dn\Delta ff_t^*$) are included.

The results are presented in Panels A, B, and C for Specification 1 of Table 1. The first column of each specification reports the parameter estimate, and the second column reports the corresponding significance level of the test that the coefficient is zero. Panel A reports the estimates of β for the parameters that are particularly relevant for evaluating the daily and policy-relevant liquidity effects. Panel B reports the estimates for the remaining parameters of β. Panel C reports the estimates of the variance parameters and the relevant summary statistics.

The estimates of the variance parameters in Panel C for Specification 1 show that the variance increased significantly during the periods immediately following the 1987 stock market crash and following the 1990 surprise reduction in reserve requirements. Also, the estimate of degrees of freedom (dof) is very small, 3.77, and highly statistically significant, indicating the appropriateness of using the Student's t distribution.

Panel B reports estimates of the "nuisance" parameters designed to account for certain day-specific effects. All but a few of these estimates are statistically significant. In most cases the estimated responses are as one might expect, e.g., the funds rate tends

[20] Hamilton and Demrialp partition *miss* by each day of the maintenance period. However, save the last two days of the maintenance period, there is no particular reason to believe that the slope of the money demand curve should be different on these days. Consequently, that practice is not followed here.

to be higher on settlement Wednesdays, higher at the end of the quarter, the first and last days of the month, etc.

Panel A reports the estimates relevant for the daily and policy-relevant liquidity effects. As expected, reserve supply shocks that occur on days when the FOMC changed the funds rate target are not statistically significant, regardless of whether the shocks are large or small. Also, consistent with Carpenter and Demiralp (2006), the response of the funds rate to small shocks on all but the last two days of the maintenance period is statistically significant and smaller than the response to large shocks. However, the magnitude of the difference between the response to large and small shocks is relatively small. Indeed, the likelihood ratio test statistic for equality of the response is 0.464, which is not statistically significant at any commonly used significance level. Hence, the evidence of nonlinearity is weak.

There is a statistically significant difference in the response of the funds rate on the last two days of the maintenance period relative to other days. Indeed, the response is considerably larger, about three times as large.

The coefficients on $BR_t - IBA_t$, k_t, and err_t^D are all statistically significant at very low significance levels. The coefficient on $BR_t - IBA_t$ is positive, suggesting that borrowing above the FOMC's assumed level is associated with the funds rate above the target. The sign of the coefficient is inconsistent with a supply shock interpretation, but is consistent with the evidence that borrowing responds endogenously to the funds rate (e.g., Thornton, 2001b). The coefficients on k_t and err_t^D have the anticipated signs. The estimated coefficient on k_t suggests that the funds rate tends to be significantly lower on days when the Desk engages in more open market operations than the operating procedure suggests. Likewise, if the Desk underestimates the demand for reserves, the funds rate is somewhat higher. Particularly interesting is the fact that the estimated coefficients on err_t^D and $miss$ on other than the last two days of the maintenance period are similar in magnitude but opposite in sign. Indeed, the likelihood ratio statistic for the hypothesis that the responses are equal but opposite in sign is 0.79. This is exactly what one would expect since a positive value of err_t^D is conceptually the same as a negative reserve supply shock.

Given the lack of statistically significant nonlinearity in the response to shocks, the model is re-estimated assuming that there is no difference in the response of the funds rate to large or small shocks. These results are reported in Specification 2 of Table 1. The estimated coefficients are nearly identical to those reported for Specification 1. Importantly, the response on the last two days of the maintenance period is three times larger than on other days.

To investigate the sensitivity of the estimates to unusually large, idiosyncratic shocks to the funds rate, the observations are partitioned into days when there are large idiosyncratic shocks to the funds rate, i.e., outliers (*O*), and days when there are no outliers (*NO*). Shocks to the funds rate are estimated by regressing the federal funds rate on a constant and the 3-month Treasury bill rate over the period. The residuals from this equation represent idiosyncratic movements in the federal funds rate. As such, the response of the funds rate on such days provides no information about a policy-relevant liquidity effect. Outliers are days when the shocks to the funds rate are more than 80 basis points (roughly two standard errors).[21] There were 62 such days during this sample

[21] As a robustness check on the qualitative results values of 40, 50, and 60 basis points were also used. The

period (slightly more than 3 percent of the days), 33 of which occurred on a settlement Tuesday or Wednesday.

Estimates with the variables partitioned by outliers are reported in Specification 3 of Table 1. As anticipated, estimates of the daily liquidity effect are sensitive to idiosyncratic shocks to the funds rate. On days when there are large idiosyncratic shocks to the funds rate, the estimated daily liquidity effect overestimates considerably the magnitude of the policy-relevant liquidity effect.

The estimate of the response on the last two days of the maintenance period when there are no outliers is also problematic for the reasons discussed in Section 2. Hence, the estimate of the daily liquidity effect that is most indicative of the policy-relevant liquidity effect is the estimate for other than the last two days of the maintenance period when there are no large, idiosyncratic shocks to the funds rate. The estimated daily liquidity effect is small and statistically significant.[22] As before, this estimate is nearly equal but opposite in sign to that on reserve demand forecast errors. Again, the null hypothesis that these coefficients are equal and opposite in sign is not rejected. The likelihood ratio statistic is 1.066.

3.1 Post-1993 Estimates of the Daily Liquidity Effect

The introduction of sweep accounts in January 1994 dramatically reduced reserve requirements for banks over time. Anderson and Rasche (2001) show that sweep activity

---

qualitative conclusion about the coefficient $miss$ on NO days is invariant to the value used.

[22] Given the close relationship between the funds rate and the funds rate target, the model was also estimated using $ff_t - ff_t^*$ as the dependent variable. While the coefficient estimates changed somewhat, the qualitative conclusions are not sensitive to whether ff_t or $ff_t - ff_t^*$ is the dependent variable. The quantitative and qualitative results are very sensitive to excluding $BR_t - IBA_t$, err_t^D, and k_t, however. The correlations between $miss$ and $BR_t - IBA_t$, err_t^D, and k_t over this sample period are -0.058, 0.352, and -0.013, respectively.

significantly reduced deposit liabilities that were subject to reserve requirements by the end of our sample period, December 31, 1996. They conclude that by the end of 1999 "the willingness of bank regulators to permit use of deposit-sweeping software has made statutory reserve requirements a 'voluntary constraint' for most banks." To investigate the effect of sweep accounts on the estimate of the daily liquidity effect, the model is estimated over the period January 3, 1994, through December 31, 1996. To conserve space, only estimates of the parameters that are relevant for the liquidity effect are reported in Table 2. All of the estimated coefficients on the various partitions of $miss$ are much smaller in absolute value than those reported in Table 1. Moreover, none is statistically significant at the 5 percent significance level. The estimate is statistically significant at slightly higher than the 5 percent significance level when $miss$ is partitioned by $nl2d$ and NO. The estimate is only about half as large as that for the pre-1994 period, which is inconsistent with expectations given that sweeps effectively reduce reserve requirements. The effective elimination of mandatory reserve requirements could have significantly altered the interest sensitivity of reserve demand independent of money demand. In any event, as before, the estimated coefficient on $miss$ for these days is equal but opposite in sign to that of reserve demand shocks.

Finally, the model was estimated over the period August 3, 1998, through January 30, 2004. It is important to note that $BR_t - IBA_t$, err_t^D, and k_t are not available over this period, so the estimates are likely to be biased. More importantly, because the introduction of lagged reserve accounting effectively severed the contemporaneous relationship between money and reserve demand, estimates of the daily liquidity effect have no implication for the policy-relevant liquidity effect. The estimate for other than the last two days of the maintenance period when there were no outliers is -0.007 and statistically significant at a very low significance level. This estimate suggests that the demand for reserves can be interest sensitive apart from the interest sensitivity of money demand.

4.0 Conclusions and Further Analysis

The daily liquidity effect was first investigated by Hamilton (1997) in an attempt to find evidence of a policy-relevant liquidity effect that had escaped detection using lower frequency, monthly and quarterly, data. The daily liquidity effect is directly linked to the policy-relevant liquidity effect because the Federal Reserve imposed reserve requirements. This paper analyzed the relationship between the policy-relevant and daily liquidity effects using a comprehensive model of the Desk's operating procedure. The analysis shows that the relationship between the daily and policy-relevant liquidity effects depends on the Desk's operating procedure, the Fed's system of reserve requirements, and other factors. Importantly, the analysis shows that there is no relationship between these liquidity effects after July 1998 when the Fed reinstated lagged reserve accounting.

Estimates of the model using data before 1994 suggest that there may have been a statistically significant policy-relevant liquidity effect prior to 1994. The estimated daily liquidity effect is very small, however. The estimate suggests that it would take roughly a $10 billion reserve supply shock to generate about a 20-basis-point change in the funds rate. If one assumes that the average effective reserve requirement during this period is 10 percent, this would be equivalent to about a $100 billion shock to the money supply. Recent research by Kuttner (2001), Poole, Rasche, and Thornton (2002) and Hamilton

(2007), shows that the effect of an exogenous change in the funds rate translates into smaller changes in other market interest rates and that the effect becomes successively smaller as the term to maturity increases.

Because banks have an incentive to economize on their holdings of reserves, reserve demand is interest sensitive after the Fed reinstated lagged reserve accounting in July 1998. Estimates of a statistically significant daily liquidity effect after July 1998, reported here and elsewhere, however, have no implications for the policy-relevant liquidity effect. They merely confirm the interest sensitivity of reserve demand.

The analysis presented here suggests that it is no easier to find convincing proof of a statistically significant and economically important policy-relevant liquidity effect using high-frequency daily data than it has been using lower frequency (monthly and quarterly) data. A resolution of the liquidity puzzle remains elusive.

References

Anderson, R.G., and R.H. Rasche. (2001). "Retail Sweep Programs and Bank Reserves, 1994-1999," Federal Reserve Bank of St. Louis *Review*, *83*(1), 51-72.

Bartolini, L., Bertola, G., and Prati, A. (2002). "Day-to-Day Monetary Policy and the Volatility of the Federal Funds Interest Rate," *Journal of Money, Credit, and Banking*, *34*(1), 137-59.

Bernanke, B.S. and Mihov, I. (1998a). "The Liquidity Effect and Long-run Neutrality," *Carnegie-Rochester Conference Series on Public Policy*, *49*, 149-94.

Bernanke, B.S. and Mihov, I. (1998b). "Measuring Monetary Policy," *Quarterly Journal of Economics*, *113*(3), 869-902.

Cagan, P. and Gandolfi, A. (1969). "The Lag in Monetary Policy as Implied by the Time Pattern of Monetary Effects on Interest Rates," *American Economic Review*, *59*(2), 277-84.

Carpenter, S., and Demiralp, S. (2006). "The Liquidity Effect in the Federal Funds Market: Evidence from Daily Open Market Operations," *Journal of Money, Credit, and Banking*, *38*(4), 901-20.

Christiano, L.J., and Eichenbaum, M. (1992). "Identification and the Liquidity Effect of a Monetary Policy Shock," in Cukierman, A., Z. Hercowitz, and L. Leiderman (Eds.) *Political Economy, Growth, and Business Cycles*, MIT Press, Cambridge, MA, 335-70.

Christiano, L.J., Eichenbaum, M. and Evans, C.L. (1996a). "The Effects of Monetary Policy Shocks: Evidence from the Flow of Funds," *Review of Economics and Statistics*, *78*(1), 16-34.

Christiano, L.J., Eichenbaum, M. and Evans, C.L. (1996b). "Identification and the Effects of Monetary Policy Shocks," in Blejer, M., Z. Eckstein, Z. Hercowitz, and L. Leiderman (Eds.) *Financial Factors in Economic Stabilization and Growth*, Cambridge University Press, Cambridge, MA, 36-74.

Clouse, J.A. and Dow, J.P. Jr. (2002). "A Computational Model of Banks' Optimal Reserve Management Policy," *Journal of Economic Dynamics and Control*, *26*(11), 1787-1814.

Coleman, J., Gilles, C. and Labadie, P., (1996). "A Model of the Federal Funds Market," *Economic Theory*, *7*(2), 337-357.

Cook, T. and Hahn, T. (1989). "The Effect of Changes in the Federal Funds Rate Target on Market Interest Rates in the 1970s," *Journal of Monetary Economics*, November, *24*(3), pp. 331-51.

Engle, R.F. (1982). "Autoregressive Conditional Heteroscedasticity with Estimates of the Variance of United Kingdom Inflation," *Econometrica*, *50*(4), 987-1007.

Evans, C.L. and Marshall, D.A. (1998). "Monetary Policy and the Term Structure of Nominal Interest Rates: Evidence and Theory." *Carnegie Rochester Conference Series on Public Policy*, *49*, 53-111.

Feinman, J.N. (1993). "Estimating the Open Market Desk's Daily Reaction Function," *Journal of Money, Credit, and Banking*, *25*(2), 231-47.

Friedman, M. (1969) "Factors Affecting the Level of Interest Rates," in Proceeding of the 1968 Conference on Saving and Residential Financing. Chicago: United States Saving and Loan League, 1969, 11-27. Reprinted in Thomas M. Havrilesky and John T. Boorman, eds., Current Issues in Monetary Theory and Policy. Arlington Heights, IL: AHM Publishing Corp., 1976, 362-78.

Gibson, W.E. (1970a). "Interest Rates and Monetary Policy," *Journal of Political Economy*, *78*(3), 431-55.

Gibson, W.E. (1970b). "The Lag in the Effect of Monetary Policy on Income and Interest Rates," *Quarterly Journal of Economics*, *84*(2), 288-300.

Hamilton, J.D. (1997), "Measuring the Liquidity Effect," *American Economic Review, 87*(1), 80-97.

Hamilton, J.D. (2007), "Assessing Monetary Policy Effects Using Daily Fed Funds Futures Contracts," Federal Reserve Bank of St. Louis *Review*, forthcoming.

Humphrey, T.M. (1983a). "The Early History of the Real/Nominal Interest Rate Relationship." Federal Reserve Bank of Richmond *Economic Review*, *69*(3), 2-10.

Humphrey, T.M. (1983b). "Can the Central Bank Peg Real Interest Rates? A Survey of Classical and Neoclassical Opinion." Federal Reserve Bank of Richmond *Economic Review*, *69*(5), 12-21.

Kuttner, K.N. (2001). "Monetary Policy Surprises and Interest Rates: Evidence from the Federal Funds Futures Market." *Journal of Monetary Economics*, *47*(3), 523-44.

Nelson, D.B. (1991). "Conditional Heteroskedasticity in Asset Returns: A New Approach," *Econometrica*, *59*(2), 347-70.

Pagan, A.R. and Robertson, J.C. (1995). "Resolving the Liquidity Effect." Federal Reserve Bank of St. Louis *Review*, *77*(3), 33-54.

Poole, W. , Rasche, R.H., and Thornton, D.L. (2002). "Market Anticipations of Monetary Policy Actions," Federal Reserve Bank of St. Louis *Review*, *84*(4), 65-94.

Strongin, S. (1995). "The Identification of Monetary Policy Disturbances: Explaining the Liquidity Puzzle," *Journal of Monetary Economics*, *35*(3), 463-97.

Thornton, D.L. (2007). "Open Market Operations and the Federal Funds Rate," in *Open Market Operations and the Financial Markets*, the Bank of Finland, reprinted in the Federal Reserve Bank of St. Louis *Review*, *89*(6), 549-72.

Thornton, D.L. (2006). "When Did the FOMC Begin Targeting the Federal Funds Rate? What the Verbatim Transcripts Tell Us," *Journal of Money, Credit, and Banking*, *38*(8), 2039-71.

Thornton, D.L. (2005). "Test of the Expectations Hypothesis: Resolving the Anomalies When the Short-Term Rate Is the Federal Funds Rate," *Journal of Banking and Finance*, *29*(10), 2541-56.

Thornton, D.L. (2004). "Forecasting the Treasury's Balance at the Fed," *Journal of Forecasting*, *23*(5), 357-71.

Thornton, D.L. (2001a). "Identifying the Liquidity Effect at the Daily Frequency," Federal Reserve Bank of St. Louis *Review*, *83*(4), pp. 59-78.

Thornton, D.L. (2001b). "The Federal Reserve's Operating Procedure, Nonborrowed Reserves, Borrowed Reserves and the Liquidity Effect," *Journal of Banking and Finance*, *25*(9), pp. 1717-39.

Thornton, D.L. (1988). "The Borrowed-Reserves Operating Procedure: Theory and Evidence, Federal Reserve Bank of St. Louis *Review 70*(1), 30-54.

Table 1: Estimates of the Reserve Market Model: January 2, 1986 – December 31, 1993

Panel A

Variable	Specification 1		Specification 2		Specification 3	
ff_t^*	0.5555	0.0000	0.5523	0.0000	0.5580	0.0000
Δff_t^*	0.0003	0.3820	0.0004	0.3238	0.0004	0.3320
$miss_t^{sm} \text{ x } d\Delta ff_t^*$	0.0104	0.5593	0.0109	0.1679	0.0106	0.1763
$miss_t^{sm} \text{ x } dn\Delta ff_t^* \text{ x } l2d$	-0.0047	0.8203				
$miss_t^{sm} \text{ x } dn\Delta ff_t^* \text{ x } nl2d$	-0.0083	0.0219				
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d$			-0.0327	0.0000		
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d$			-0.0109	0.0000		
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } O$					-0.2181	0.0000
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } NO$					-0.0275	0.0001
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } O$					-0.1195	0.0049
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } NO$					-0.0108	0.0000
$miss_t^{\lg} \text{ x } d\Delta ff_t^*$	0.0113	0.1887				
$miss_t^{\lg} \text{ x } dn\Delta ff_t^* \text{ x } l2d$	-0.0323	0.0000				
$miss_t^{\lg} \text{ x } dn\Delta ff_t^* \text{ x } nl2d$	-0.0114	0.0000				
$BR_t - IBA_t$	0.0243	0.0000	0.0239	0.0000	0.0239	0.0000
err_t^D	0.0088	0.0000	0.0089	0.0000	0.0088	0.0000
k_t	-0.0048	0.0003	-0.0046	0.0005	-0.0047	0.0004

Table 1 Continued						
	Panel B					
Variable	Specification 1		Specification 2		Specification 3	
ff_{t-1} x $w1$	0.4472	0.0000	0.4504	0.0000	0.4447	0.0000
ff_{t-1} x $w2$	0.4461	0.0000	0.4494	0.0000	0.4436	0.0000
$D1$	-0.0132	0.2335	-0.0126	0.2555	-0.0130	0.2425
$D2$	-0.0556	0.0000	-0.0691	0.0000	-0.0683	0.0000
$D3$	0.0468	0.0000	0.0340	0.0001	0.0342	0.0001
$D4$	-0.0287	0.0015	-0.0414	0.0000	-0.0413	0.0000
$D5$	-0.0351	0.0001	-0.0482	0.0000	-0.0482	0.0000
$D6$	0.0053	0.6869	-0.0085	0.2980	-0.0077	0.3445
$D7$	-0.0514	0.0001	-0.0649	0.0000	-0.0640	0.0000
$D8$	0.0542	0.0006	0.0398	0.0006	0.0403	0.0004
$D9$	-0.0399	0.0224	-0.0537	0.0001	-0.0524	0.0002
$D10$	0.0817	0.0000	0.0678	0.0000	0.0690	0.0000
eom	0.0871	0.0000	0.0861	0.0000	0.0881	0.0000
bom	0.0572	0.0000	0.0573	0.0000	0.0570	0.0000
eoq	0.2125	0.0032	0.2159	0.0028	0.2000	0.0035
boq	-0.1152	0.0070	-0.1176	0.0056	-0.1202	0.0035
eoy	-0.3804	0.0003	-0.3810	0.0003	-0.3675	0.0004
boy	0.4270	0.0006	0.4301	0.0005	0.4351	0.0005
mom	0.0899	0.0000	0.0904	0.0000	0.0903	0.0000
bh	-0.0169	0.0329	-0.0163	0.0398	-0.0173	0.0297
ah	0.1097	0.0000	0.1094	0.0000	0.1095	0.0000

Table 1 Continued						
Panel C						
Variables	Specification 1		Specification 2		Specification 3	
const.	-3.0817	0.0000	-3.0848	0.0000	-3.0208	0.0000
$\lvert\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\rvert$	0.7053	0.0000	0.7043	0.0000	0.6821	0.0000
$\frac{\varepsilon_{t-1}}{\sigma_{t-1}}$	0.0559	0.2237	0.0585	0.2058	0.0638	0.1507
$\log \sigma_{t-1}^2$	0.5387	0.0000	0.5374	0.0000	0.5466	0.0000
$D1+D2+D3$	1.5364	0.0000	1.5356	0.0000	1.5135	0.0000
btar	0.6902	0.0085	0.6768	0.0086	0.6660	0.0097
ah	1.1983	0.0000	1.2091	0.0000	1.1562	0.0000
eom	0.9886	0.0000	-1.8576	0.0096	-1.6951	0.0161
eoq	2.4000	0.0000	2.4184	0.0000	2.3238	0.0000
eoy	-1.8168	0.0108	0.9883	0.0000	0.9508	0.0000
mom	0.6470	0.0028	0.6558	0.0024	0.6322	0.0033
$d1987$	0.4993	0.0239	0.4942	0.0251	1.3252	0.0000
$d1990$	1.3196	0.0000	1.3238	0.0000	0.5740	0.0099
dof	3.7653	0.0000	3.7529	0.0000	3.7440	0.0000
No. of Obs.	1966		1966		1966	
$\bar{R}^2$	0.9887		0.9885		0.9892	
s.e.	0.2234		0.2244		0.2180	
Log Likelihood	1477.061		1475.596		1479.130	

Table 2: Estimates of the Reserve Market Model: January 3, 1994 - December 31, 1996.		
Variable	Coefficient	Significance Level
ff_t^*	0.769	0.000
Δff_t^*	-0.000	0.820
$miss_t^{sm}$ x $d\Delta ff_t^*$	0.769	0.000
$miss_t$ x $dn\Delta ff_t^*$ x $l2d$ x O	0.000	0.820
$miss_t$ x $dn\Delta ff_t^*$ x $l2d$ x NO	-0.008	0.881
$miss_t$ x $dn\Delta ff_t^*$ x $nl2d$ x O	-0.011	0.281
$miss_t$ x $dn\Delta ff_t^*$ x $nl2d$ x NO	-0.004	0.051
$BR_t - IBA_t$	0.198	0.000
err_t^D	0.004	0.006
k_t	0.000	0.770
No. of Obs.	754	
$\overline{R}^2$	0.946	
s.e.	0.197	
Log Likelihood	789.248	

Figure 1 Effective Federal Funds Rate and the FOMC's Funds Rate Target
(January 2, 1986 - January 20, 2004)